ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 39 (2013) 183 – 192
Energy Procedia

Asian Nuclear Prospects 2012

(ANUP2012)

Analysis for Impact of Seismic Capacity Uncertainty on System Reliability

YU Yu*, QIAN Xiaoming, WANG Shengfei, LV Xuefeng, NIU Fenglei,LIU Yu

School of Nuclear Science and Technology,North China Electric Power Universit,y
No.2 Beinong Road, Huilongguan,Zhuxinzhuang, Changping District,, Beijing, 102206, China

Abstract

It is important for nuclear power plant safety whether the safety system can work well or not in seismic condition. Seismic capacity data are important parameters to describe the component reliability, based on which the High Confidence, Low Probability of Failure (HCLPF) for component can be obtained by seismic margin evaluation. However, other than median ground acceleration capacity, the aleatory and epistemic uncertainties are also key factors for component reliability, so the seismic hazard curve is one of the important affecting factors and should be taken into account in the system reliability analysis. In this paper, passive residual heat removal system in AP1000 is calculated as an example, Fault Tree(FT) method is used to analyze the system reliability at different ground acceleration levels, the contribution to the system failure of components having different uncertainty parameters are given. And Monte Carlo(MC) simulation is used to evaluate the system reliability in seismic situation based on different seismic hazard curves, the effect of seismic hazard curve and seismic capacity uncertainty are put forward. Then the following conclusion is gotten: since the impact of seismic capacity uncertainty on the system reliability is affected by the relationship between the median ground acceleration capacity of the component and the ground acceleration level, that is, when the median ground acceleration capacity of the component is much higher than the ground acceleration level, the higher is the uncertainty, the higher is the component failure probability, when the median ground acceleration capacity of the component is close to or even higher than the ground acceleration level, the component seismic capacity uncertainty may decrease the component failure probability, so the system reliability and the main contributors are decided by the seismic capacity data and seismic hazard curve synthetically.

Keywords: seismic capacity uncertainty; seismic hazard curve,; system reliability; MC simulation; fault tree

* Corresponding author. Tel.: +86-10-51963820; fax: +86-10-51963357.
E-mail address: yuyu2011@ncepu.edu.cn.

doi:10.1016/j.egypro.2013.07.205

1. Main text

More attention is paid to nuclear power plant safety under seismic situation in recent years, especially after Fukushima nuclear accident. In seismic probabilistic safety assessment (PSA), more effort is paid to the risk-based seismic margin analysis [1,2,3,4], in which the value of High Confidence, Low Probability of Failure (HCLPF) is used to evaluate the seismic margin of the equipment. From the mathematical perspective of a probability distribution on capacity developed in seismic PSA calculation, the HCLPF capacity value is approximately equal to a 95% confidence of not exceeding about a 5% probability of failure. From the definition, it can be seen that the HCLPF of the equipment is higher, the seismic capacity is better. However, in the seismic margin analysis, the effect of the uncertainty of seismic capacity is not fully taken into account, and the failure probability of the system cannot be gained. In this paper, Fault Tree(FT) method is used to analyze the system reliability at different ground acceleration levels, the contribution to the system failure of components having different uncertainty parameters are given. And Monte Carlo (MC) simulation [5,6] is used to evaluate the system reliability in seismic situation based on different seismic hazard curves, the effect of seismic hazard curve and seismic capacity uncertainty are put forward. In section 2, system reliability model under earthquake is described, in section3, passive residual heat removal (PRHR) system in AP1000 [7,8] is introduced, the results are shown in section4 and the conclusions are given in section5.

Nomenclature

CCF	Common cause failure
MC	Monte Carlo
FT	Fault Tree
HCLPF	High Confidence, Low Probability of Failure
PRHR	Passive residual heat removal system
PSA	Probabilistic Safety Assessment

2. System reliability analysis model under earthquake

2.1. Component failure model

The component failure probability under earthquake can be described as formula (1) [1]

$$f = \phi(\ln(\frac{a}{Am}) / B_R) \tag{1}$$

Where,

- f — component failure probability under earthquake
- a — peak ground acceleration level
- Am — median ground acceleration capacity
- B_R — randomness between earthquake and effects

- $\Phi(\bullet)$ — standard Gaussian cumulative distribution function

From formula (1), it can be seen that component failure probability under seismic situation is the function of component seismic capacity (Am and B_R) and peak ground acceleration level (a), which is conditional probability.

Effect of uncertainty is different for different levels of a/Am, Fig.1 shows the relationship between equipment failure probability f and uncertainty B_R based on different values of a/Am.

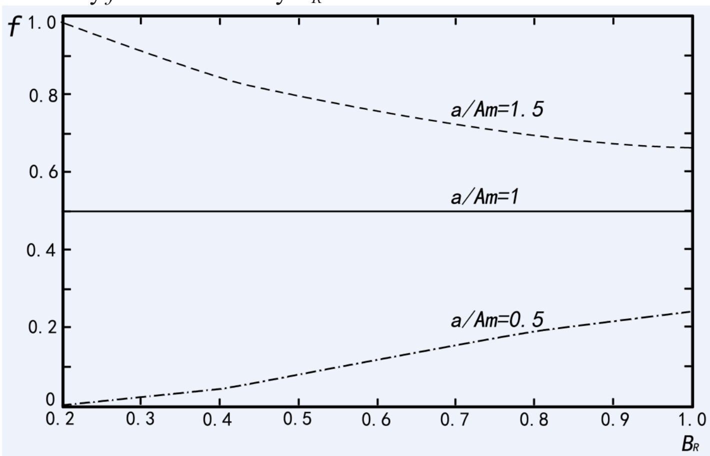

Fig. 1. Effect of B_R based on a/Am

From Fig.1, it can be seen that when a/Am = 0.5, equipment failure probability increases with uncertainty increasing, and when a/Am = 0.5, equipment failure probability decreases with uncertainty increasing. It can be explained as following:

- When $a < Am$, that is, peak ground acceleration level is smaller than equipment median ground acceleration capacity, so the uncertainty is larger, the equipment failure probability is higher.
- When $a > Am$, that is, peak ground acceleration level is higher than equipment median ground acceleration capacity, so the uncertainty is larger, the equipment failure probability is lower.
- When $a=Am$, uncertainty has no effect on equipment failure probability.

Since the uncertainty has different effect when a/Am has different values, a is a stochastic value whose distribution is determined by seismic hazard curve, so the seismic hazard curve is an important influence key for system reliability under earthquake.

2.2. System reliability model

System reliability depends on the component reliability and system configuration. Since component failure probability is conditional probability of peak ground acceleration level (a) which is a stochastic number according with the given probabilistic density distribution, the MC simulation can be used to evaluate the system reliability. The peak ground acceleration level (a) distribution can be gotten from the seismic hazard curve, and the flow chart of MC simulation is shown in Fig.2

3. Passive residual heat removal system in AP1000

The passive residual heat removal (PRHR) system [7] is a subsystem the passive core cooling system, and the function of PRHR system is to provide emergency core decay heat removal during transients,

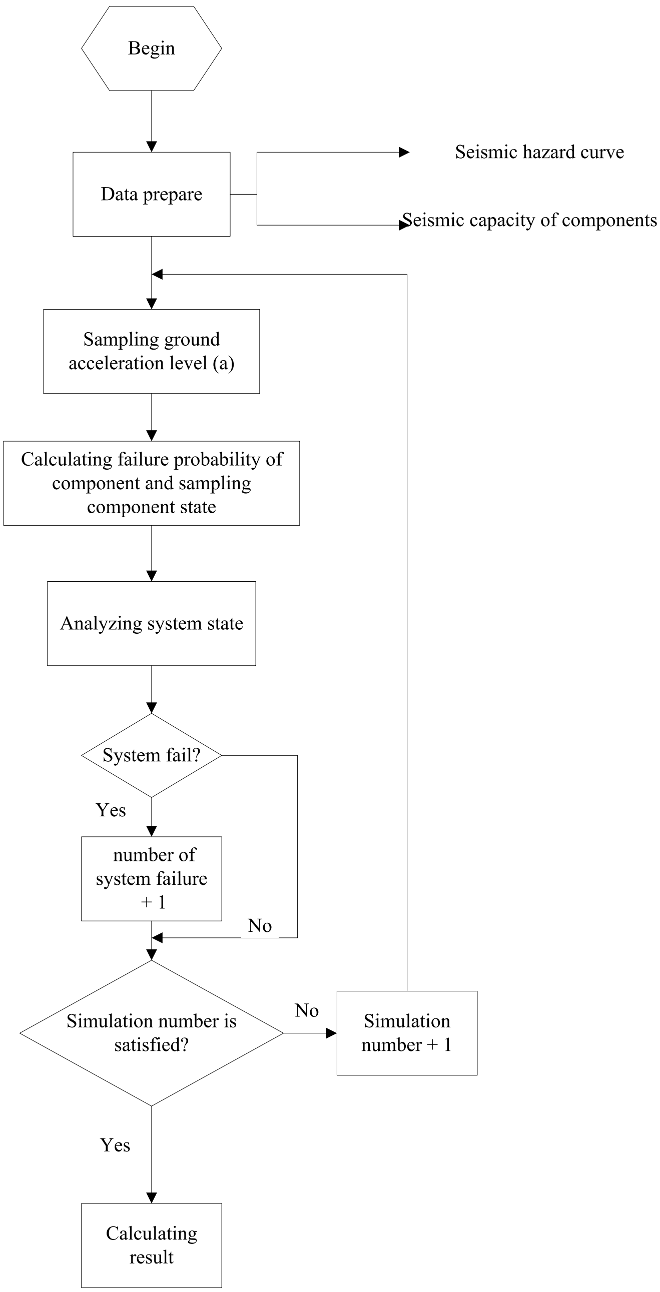

Fig. 2. Flow chart of MC simulation

accidents, or whenever the normal heat removal system paths via the steam generator are lost. The system consists of one PRHR heat exchanger (PRHR HX) and associated valves. The heat exchanger is located in the in-containment refueling water storage tank (IRWST) which provides the heat sink. And the heat exchanger is maintained full of cold reactor coolant at full RCS pressure, which connects to the cold reactor coolant system (RCS) by an inlet line from one RCS hot leg with a normally open motor-operated isolation valve that connects to the upper PRHR heat exchanger channel head, and by an outlet line from the PRHR heat exchanger to the RCS cold leg with two parallel, normally closed air-operated valves, the valves open upon loss of air pressure or on control actuation signal. And the heat exchanger is elevated above the RCS loops to induce natural circulation flow when the RCS pumps are not available.

The IRWST gutter circumnavigates the containment shell, the purpose of which is to collect condensed water on the containment shell and, in the event of PRHR actuation, return the water to the IRWST. Under normal conditions, two sequent air-operated valves at the outlet line of the gutter are open and the gutter sends excess condensate to the liquid radwaste system containment sump. During events with PRHR actuation, the air-operated valves close to shut off access to the waste sump, thus the water is returned to the IRWST, allowing the PRHR heat exchanger to remain submerged in water. The flow of the PRHR system is shown in Fig.3 [7].

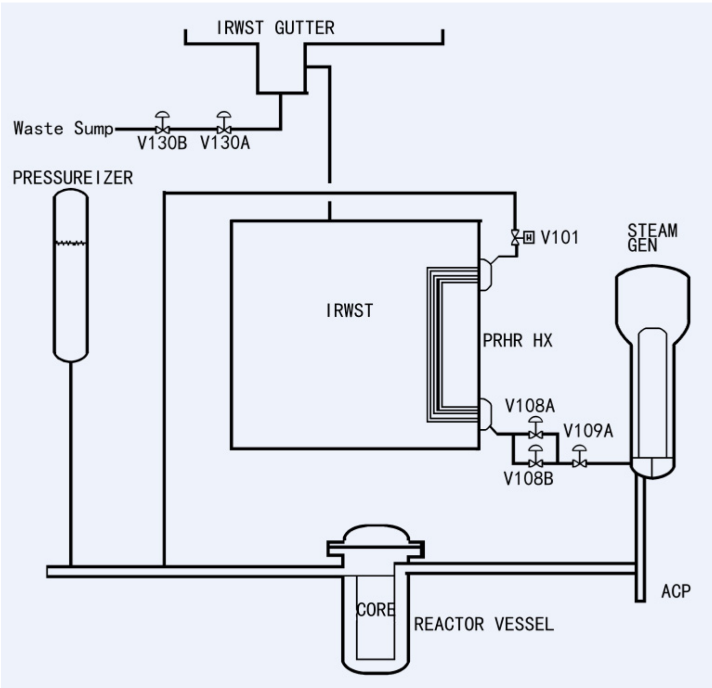

Fig. 3. Flow of Passive Residual Heat Removal System in AP1000

4. Results

In this paper, FT and MC methods are used to evaluate the reliability of passive residual heat removal system, component failure due to earthquake and stochastic events are included, component failure data and seismic capacity data are shown in Table 1[7] and Table 2[9], and common cause failure (CCF) factor is 0.1 for stochastic failure and 1.0 [10] for failure due to earthquake.

Table 1. Component failure data

Component	Fail to open/close (1/Demand)	Operation failure (1/h)
IRWST	/	1.0E-7
PRHR HX	/	1.0E-7
VALVE	1.1E-3	1.0E-6

Table 2. Component seismic capacity data

Component	Ground acceleration capacity Am (g)	Uncertainty B_R (g)	HCLPF (g)
IRWST	1.3	0.42	0.50
PRHR HX	2.2	0.46	0.76
VALVE	3.3	0.61	0.81
STEAM GEN.	0.98	0.26	0.54

4.1. FT analysis

FT method is used to analyze the system reliability under two conditions: the peak ground acceleration is 0.5g and 1 g. The fault tree for PRHR system reliability analysis is shown in Fig.3.

When the peak ground acceleration (a) is 0.5g, the system failure probability is 2.3e-2, the main contributors are shown in Table 3. And when the peak ground acceleration increases to 1g, the system failure probability is 7.0e-1, the main contributors are shown in Table 4.

Table3. Results for a=0.5g

Failure mode	Failure probability	Contribution
IRWST failure due to earthquake	1.1e-2	45%
STEAM GEN failure due to earthquake	4.8e-3	20%

Table4. Results for a=1g

Failure mode	Failure probability	Contribution
STEAM GEN failure due to earthquake	5.3e-1	76%
IRWST failure due to earthquake	2.7e-1	39%
PRHR HX failure due to earthquake	4.3e-2	6.2%

From the results, it can be seen that when the peak ground acceleration (a) is 0.5g which is lower than the component seismic capacity, the probability of IRWST failure due to earthquake is higher than that of steam generator, though the ground acceleration capacity of IRWST is higher than that of steam generator, since the uncertainty of IRWST is higher. And when the peak ground acceleration (a) increases to 1g, the probability of IRWST failure due to earthquake is lower than that of steam generator, since the peak ground acceleration is close to the ground acceleration capacity of IRWST and steam generator, so the influence of uncertainty is much lower than when a=0.5g

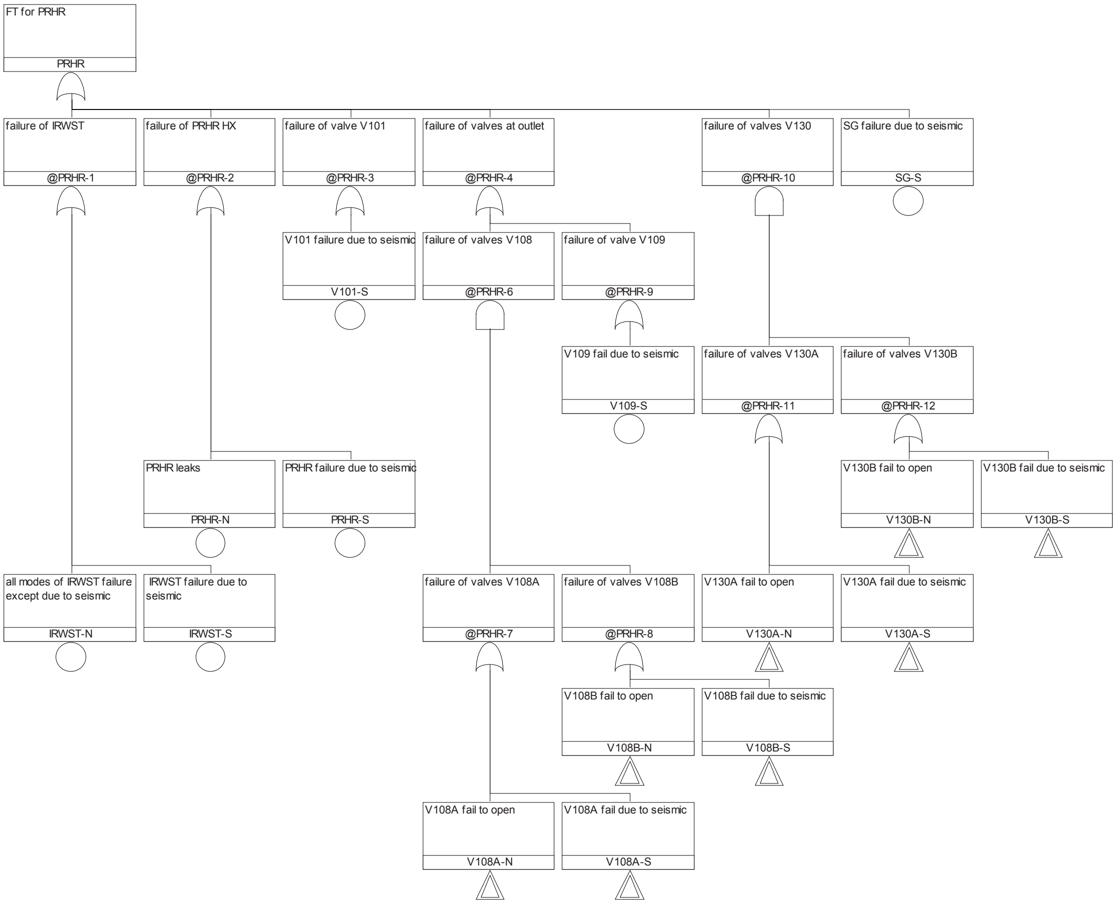

Fig. 4. FT for PRHR in AP1000

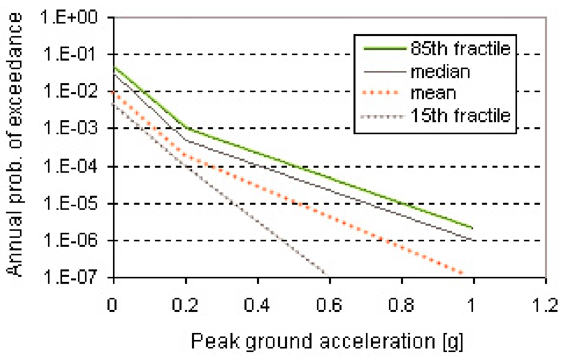

Fig. 5. Seismic hazard curve I

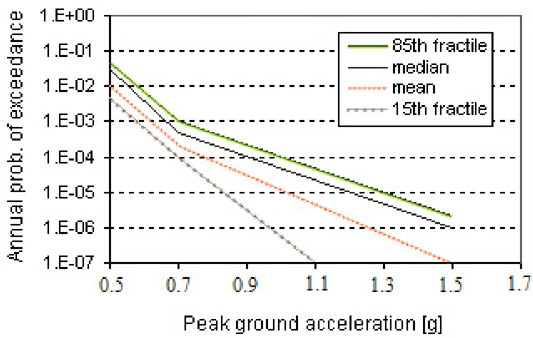

Fig. 6. Seismic hazard curve II

Table 5. Results for seismic hazard curve in Fig.5

Component Failure Mode	Failure Probability	Contribution
IRWST fails during operation	2.0e-6	0.44%
PRHR HX fails during operation	3.0e-6	0.67%
The valve at the heat exchanger inlet line fails due to stochastic event	2.3e-5	5.1%
Both of the valves at the heat exchanger outlet line fail to open (CCF)	1.3e-4	29%
Both of the valves at the heat exchanger outlet line fail during operation (CCF)	1.0e-6	0.22%
Both of the valves at the IRWST gutter outlet line fail to close(CCF)	1.0e-4	22%
Both of the valves at the IRWST gutter outlet line fail during operation(CCF)	6.0e-6	1.3%
IRWST fails due to earthquake	9.2e-5	20%
PRHR HX fails due to earthquake	1.3e-5	2.9%
STEAM GEN. fails due to earthquake	5.3e-5	12%
The valve at the heat exchanger inlet line fails due to earthquake	1.1e-5	2.4%
Both of the valves at the heat exchanger outlet line fail due to earthquake (CCF)	1.1e-5	2.4%
Both of the valves at the IRWST gutter outlet line fail due to earthquake(CCF)	1.2e-5	2.7%

Table 6. Results for seismic hazard curve in Fig.6

Component Failure Mode	Failure Probability	Contribution
IRWST fails during operation	1.0e-6	0.019%
PRHR HX fails during operation	2.0e-6	0.037%
The valve at the heat exchanger inlet line fails due to stochastic event	2.8e-5	0.6%
Both of the valves at the heat exchanger outlet line fail to open (CCF)	1.1e-4	2.0%
Both of the valves at the heat exchanger outlet line fail during operation (CCF)	2.0e-6	0.037%
Both of the valves at the IRWST gutter outlet line fail to close(CCF)	1.1e-4	2.0%
Both of the valves at the IRWST gutter outlet line fail during operation(CCF)	1.0e-6	0.019%
IRWST fails due to earthquake	2.0e-3	37%
PRHR HX fails due to earthquake	3.5e-4	6.5%
STEAM GEN. fails due to earthquake	3.1e-3	57%
The valve at the heat exchanger inlet line fails due to earthquake	2.8e-4	5.2%
Both of the valves at the heat exchanger outlet line fail due to earthquake (CCF)	2.6e-4	4.8%
Both of the valves at the IRWST gutter outlet line fail due to earthquake (CCF)	2.7e-4	5.0%

4.2. MC analysis

MC method is used to analyze the system reliability under two seismic hazard curves shown in Fig.4[11] and Fig.5. In order to analyze the impact of uncertainty under different seismic hazard curves, the peak ground acceleration in Fig.4 is higher than in Fig.3 by 0.5g.

The results of system reliability analysis for Fig 5 and Fig 6 are shown in Table 5 and Table 6. System failure probability is 4.5e-4 for seismic hazard curve in Fig.5, and is 4.7e-3 for seismic hazard curve in Fig.6. In order to improve the calculation efficiency, the simulation times is chosen to get the exact value of system reliability, since some failure mode probability is very low, so the calculation error is a little high, such as operation failure modes, which are not important to system failure. In Table 5 and Table 6, the sum of all failure mode probability is a little higher than the system probability, since two or more failure modes can occur in the same round of simulation.

In Fig.4, peak ground acceleration whose probability is higher is lower than component seismic capacity, since the uncertainty of IRWST is higher than that of steam generator the failure probability of IRWST due to earthquake is higher than that of steam generator though ground acceleration capacity of IRWST is a little higher. As peak ground acceleration increasing, in some rounds of simulation the peak ground acceleration can be close to or even more than component seismic capacity data of IRWST and steam generator, so in the results shown in Table 6 the failure probability of IRWST due to earthquake is lower than that of steam generator.

5. Conclusions

In this paper, uncertainty influence on system reliability is analyzed. The results are generally according with the result of AP1000 seismic margin evaluation, the failure probability of component with higher HCLPF is lower. However, since the effect of uncertainty is related to the ratio of peak ground acceleration and component ground acceleration capacity, so the seismic hazard curve is an important key to be considered in system reliability analysis. For the same system in different places whose seismic hazard curve are different, the system reliability and the main contributors to system failure under earthquake may be different.

Acknowledgements

The work of this paper is funded by “The National Natural Science Foundation of China (51206042)” and “the Fundamental Research Funds for the Central Universities (12ZX05)”

References

[1] R J. Budnitz, P.J.Amico, C.A.Comell, et al..*An Approach to the Quantification of Seismic Margins in Nuclear Power Plants(NUREG/CR-4334).* Washington, D.C.: U.S. Nuclear Regulatory Commission; 1985

[2] L.E. Cover, M.P. Bohn, R.D. Campbell, et al.. *Handbook of Nuclear Power Plant Seismic Fragilities (NUREG/CR-3558).* Washington, D.C.: U.S. Nuclear Regulatory Commission.; 1985

[3] Shibata,H., Lappa, D., Pinto,P.,et al.. *Probabilistic safety assessment for seismic events (IAEA-TECDOC-724).* Vienna, Austria: International Atomic Energy Agency; 1993.

[4] Brendon Archie Bradley. *STRUCTURE-SPECIFIC PROBABILISTIC SEISMIC RISK ASSESSMENT.* Christchurch, New Zealand: University of Canterbury; 2009

[5] Yu YU, Jiejuan TONG, Tao LIU, et al...A MODEL FOR PASSIVE SYSTEM RELIABILITY ANALYSIS. In: *Proc. ICONE18 Conf.* , Xi'an, China; 2010

[6] Zio, E., Pedroni, N.. Estimation of the functional failure probability of a thermal-hydraulic passive system by Subset Simulation. *Nuclear Engineering and Design* ,2009; **239**:580-599.

[7] J.L.Foret.. *AP1000 Probabilistic Safety Assessment, chapter 8*.Pittsburgh, PA: Westinghouse Electric Company LLC; 2003.

[8] T.L.Schulz. Westinghouse AP1000 advanced passive plant. *Nuclear Engineering and Design*, 2006; **236**: 1547-1557

[9] J.L.Foret.. *AP1000 Probabilistic Safety Assessment, chapter 55*.Pittsburgh, PA: Westinghouse Electric Company LLC; 2003.

[10] Tadakuni Hakata. Seismic PSA method for multiple nuclear power plants in a site. *RELIABILITY ENGINEERING & SYSTEM SAFETY*, 2007; **92**: 883-894

[11] O. Nusbaumer. *Analytic Solution of Seismic Probabilistic Risk Assessment.*. In: *Proc. ESREL Conf*.,Tri City Poland.; 2005